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High-Fidelity Analog Fiber Optics and Photonics for Military Applications

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Introduction: Radio-frequency (RF) photonics provides increased or previously unavailable capabilities for many military platforms and applications. As compared to electronic approaches, photonics offers increased transmission distances in antenna-remoting applications, unrivaled bandwidth in signal-processing and other electromagnetic-warfare applications, and decreased size and weight in numerous military platforms. In addition, fiber optics as a transmission medium offers invulnerability to electromagnetic interference and near-complete electrical isolation.

We describe advances in the theoretical understanding of analog-photonic systems made at NRL in 2007, along with the accompanying record-setting performance demonstrated in our experiments. We have applied our expertise to the design and implementation of two state-of-the-art prototype systems for military antenna-remoting and electromagnetic-warfare applications. Each of these prototypes and their significance are described below.

Theoretical and Experimental Analysis: The three most important metrics for an analog-photonic system are RF gain, RF noise figure, and spurious-free dynamic range (SFDR). Understanding the relationship between these traditionally employed electronic metrics and the underlying optics in a RF photonic system is crucial to maximizing performance. We have

significantly advanced the understanding of these relationships using the two new concepts of generalized relative intensity noise and the optical amplifier noise penalty.^{1,2} The generalized relative intensity noise formalism allows for a convenient analytical description of RF photonic systems in terms of the experimentally determined parameters.¹ We have formulated all of the RF performance metrics for optically intensity- and phase-modulated analog photonic links, demonstrating unique and previously unrealized advantages afforded by an optical phase modulation format.¹ We conceived and employ the noise penalty metric to describe the effect that optical amplification has on the RF performance of a fiber-optic system.² Prior to the advent of the noise penalty metric, this relationship was not clearly understood by the community as a whole. We have also presented a novel graphical approach used to describe the design tradeoffs that exist between the RF performance metrics in an intensity-modulated analog-photonic link.³

We have applied our theories to demonstrate two record-setting experiments at NRL, the measured results of which are shown in Fig. 1. We have achieved the largest signal gain demonstrated to date in an analog-photonic link at any frequency and have recorded 44 dB of signal gain above 1 GHz. For the record-setting gain experiment, we used a suppressed-carrier modulation format with strong optical amplification. We have also demonstrated the first noise figure below 10 dB in the 1 to 10 GHz range using a balanced intensity-modulated link.⁴ Both of these experiments served to broaden the scope of RF photonic applications.

High Dynamic-Range Optical Links for Antenna Remoting: We have designed and demonstrated a novel fiber-optic link for high-frequency (HF, 2 to 30 MHz) antenna remoting with a SFDR = 117 dB·Hz^{2/3} at 30

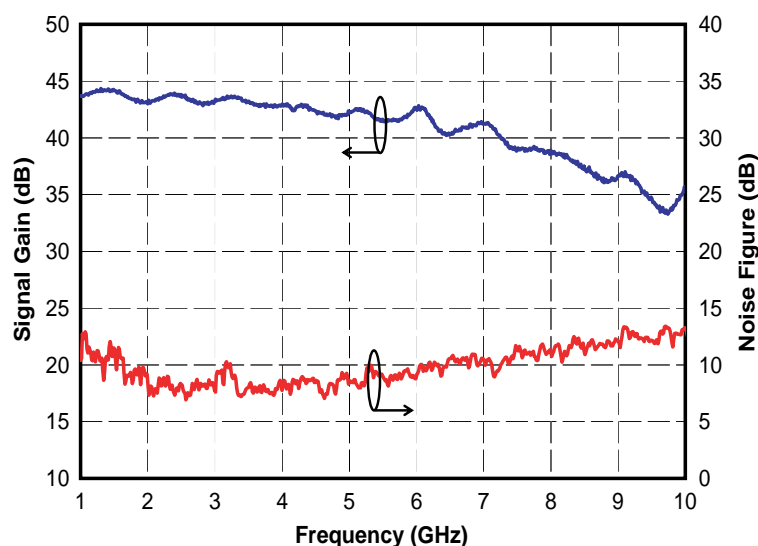


FIGURE 1

The measured results from two separate record-setting experiments. The highest signal gain for a photonic link reported to date is shown in blue and the first sub-10-dB noise figure in the 1 to 10 GHz range for a photonic link is shown in red.

MHz. Prior to our work this year, HF collection sites could be separated a maximum distance of 300 m from the signal-processing and storage facilities, limited by the loss in electronic cabling. This severely restricted placement of the collection sites because the signal-processing and storage facilities must be protected whereas the HF antennas themselves are relatively expendable. We have produced a prototype fiber-optic link for HF antenna remoting that maintains system performance and is capable of a 7-km transmission distance, a 23-fold increase in capability (Fig. 2). A

complete system employing this design is scheduled for deployment in February 2008 and will feed actionable intelligence directly to the U.S. Southern Combatant Command. This specific intelligence would not be available without the novel fiber-optic link, and no other fiber-optic link provides this capability.

Analog Optical Delay Lines for Electromagnetic Warfare: An analog optical delay line is employed to store an RF spectrum in the fiber itself for a time defined by the fiber length and speed of light in fiber.

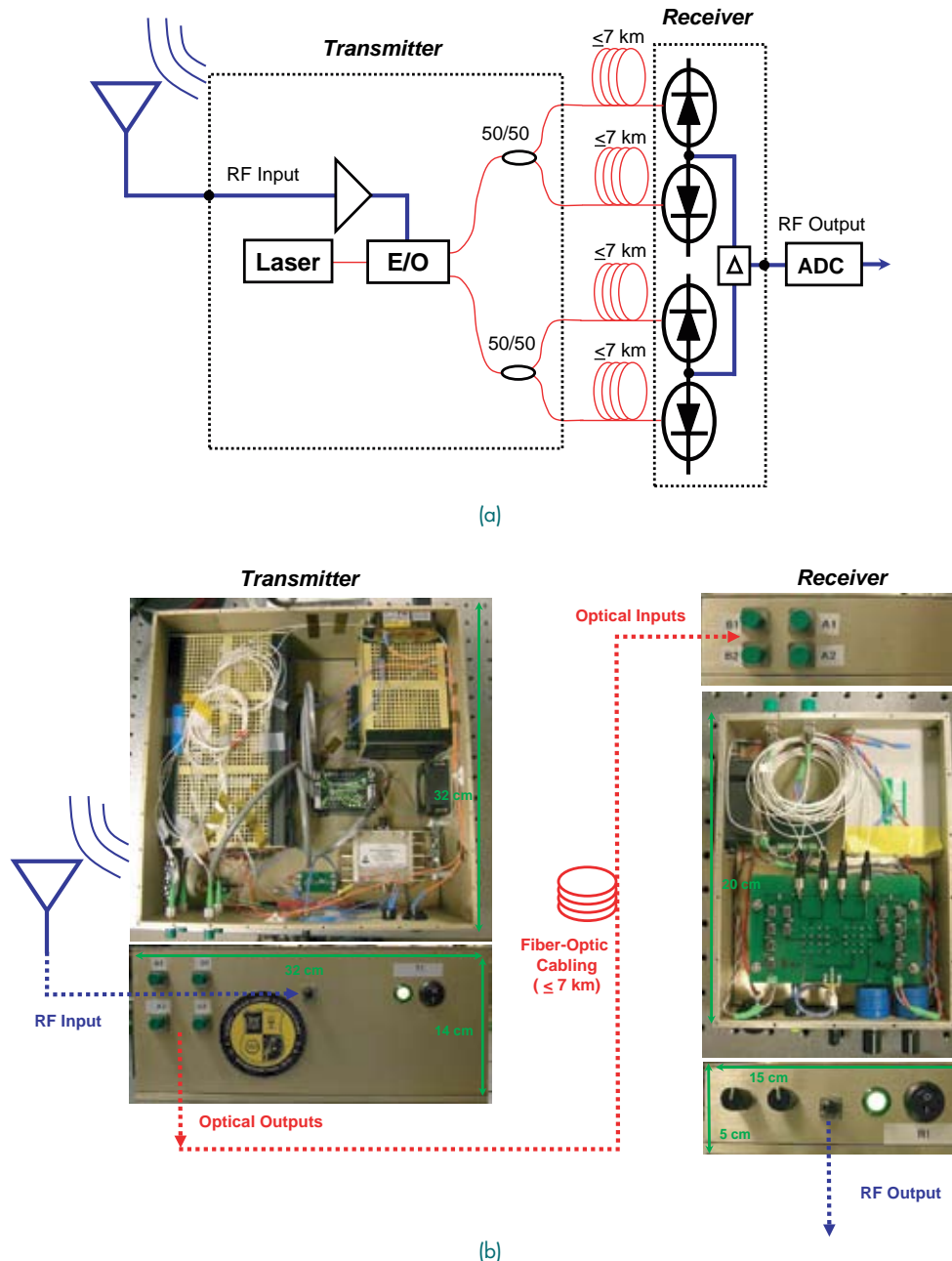


FIGURE 2

The (a) schematic and (b) photograph of a custom fiber-optic link for antenna-remoting applications. The electrical paths are shown in blue and the optical paths are shown in red. (E/O is electrical-to-optical conversion; ADC is analog-to-digital converter.)

We have demonstrated a state-of-the-art 60-km (300- μ s) optical delay line with a SFDR = 108 dB·Hz^{2/3} at 1 GHz. We have demonstrated and delivered hardware prototypes based on these optical delay lines in 2007 (Fig. 3). Electromagnetic-warfare systems that rely on these technologies are scheduled to be mass produced and deployed. These systems significantly enhance the signal-processing capabilities of the U.S. military, leveraging the bandwidth advantages of fiber optics over analog-to-digital converter technology.

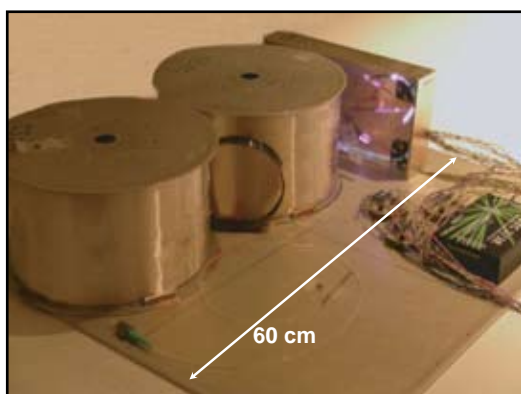


FIGURE 3

Photograph of a 60-km analog optical delay line with a custom optical amplifier for electromagnetic-warfare applications. Each spool contains 30 km (~19 miles) of optical fiber. The green emission shown in the optical amplifier box is due to an optical transition in the gain medium (the optical signal wavelength is 1550 nm). The purple is not visible to the naked eye and is attributed to the camera's response to pump light at 980 nm.

Summary: We have demonstrated significant advancements in the theoretical understanding of RF photonic and fiber-optic systems, including the generalized relative intensity noise formalism, the noise penalty metric, the analytical analysis of phase-modulated and suppressed-carrier modulation formats, and a novel graphical description of performance tradeoffs. Our expertise has allowed for the experimental demonstrations of the highest signal gain reported to date and the first noise figure below 10 dB in the 1 to 10 GHz range. In addition, we have designed and implemented two RF photonic prototype systems for antenna-remoting and electromagnetic-warfare applications. Both of these systems provide new solutions to important military problems and ultimately increase the technological advantage of the U.S. military.

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